Methods for Estimating Low-Flow Characteristics of Ungaged Streams in Selected Areas, Northern Florida

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilomete (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s)	0.646	millon gallons per day (Mgal/d)

GLOSSARY

Technical and tatistical terms are defined below with respect to applications described in this report.

ARC/INFO.--A Geographical Information System (GIS) used to develop computer coverages that quantify selected basin characteristics used in regression analyses.

Base flow.--Sustained low flow of a stream. In most places, base flow is groundwater inflow to the stream channel.

Continuous-record gaging station.--A site on a stream used to systematically record river stages for determining daily mean discharge.

Correlation.--A process by which the degree of association between two or more variables is defined.

Cubic feet per second (ft^3/s).--A unit expressing volume per unit time. One cubic foot per second is equivalent to the discharge of a stream whose channel is one square foot in cross sectional area and whose average velocity is one foot per second.

Index station.--A long-term continuous-record gaging station that is used to evaluate regional flow conditions.

Low-flow characteristic.--A statistic that describes the annual minumum average discharge for a selected consecutive-day period for a given recurrence interval in years. For example, a 7-day, 10-year low-flow characteristic ($Q_{7,10}$) of 18 ft^3/s for a site indicates that the annual minimum average discharge for 7-consecutive days is equal to or less than 18 ft^3/s once in 10 years on average; or, that there is a 10 percent chance in any year that the minimum average flow for a 7-consecutive-day period will be equal to or less than 18 ft^3/s.

Mean.--The arithmetic average of the sample.

Miscellaneous site.--A site other than a continuous- or partial-record station where discharge measurements are made for special projects, or during droughts or floods to provide improved areal coverage of hydrologic conditions.

N-day, T-year low flow ($Q_{N,T}$).--A specific frequency characteristic associated with a consecutive-day average period of N-days and a recurrence interval of T years. See low-flow characteristic.

Partial-record station.--A site where limited streamflow data are collected systematically over a prescribed period of time for use in hydrologic analyses. Type of sites include low-flow partial-record stations, periodic measurement stations, and crest-stage partial-record stations. In this report, continuous-record gaging stations that were operational for less than 10 years were considered as partial-record stations.

Recurrence interval.--The average interval of time between occurrences of a low flow less than or equal to a specified N-day low flow.

Regression.--A statistical technique for describing the relation between a response variable and an explanatory variable.

Standard error.--A measure of the dispersion of a statistic. In this report standard errors of low-flow frequency characteristics are given as a percentage, and represent the average of positive and negative departures of estimates of low-flow frequency characteristics from the mean value of the low-flow frequency characteristics.

Synoptic-measurement run.--A data-collection effort in which streamflow measurements are made to determine low-flow conditions as they exist simultaneously over a basin.

Methods for Estimating Low-Flow Characteristics of Ungaged Streams in Selected Areas, Northern Florida

***By* Roger P. Rumenik *and* J.W. Grubbs**

ABSTRACT

Methods for estimating low-flow frequency characteristics at ungaged sites were developed for two areas in northern Florida. In the Yellow, Blackwater, Escambia, and Perdido River Basins study area (northwestern Florida), regional regression equations were developed for estimating the 7- and 30-day, 2- and 10-year low-flow characteristic ($Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$) by determining values of basin characteristics from digital Geographical Information System (GIS) coverages or hardcopy maps. A GIS, ARC-INFO, was used to quantify basin characteristics that were used in regression equations. Sources of digital data used in this analysis are elevation data, from a digital elevation model, stream length and location data from a digital hydrography coverage, and watershed boundaries digitized from topographic maps.

The most accurate regression equations employed a basin characteristic that was based on a simple conceptual model of one-dimensional ground-water flow using Darcy's law. Slightly less accurate equations were obtained using drainage area as the only explanatory variable. The standard error of prediction for the Darcy and drainage area equations of $Q_{7,2}$ was 65 and 74 percent, respectively; $Q_{7,10}$, 58 and 62 percent, respectively; $Q_{30,2}$, 51 and, 54 percent, respectively; and $Q_{30,10}$, 44 and 51 percent, respectively.

In the Santa Fe River Basin study area (northeastern Florida), a flow-routing method was used to estimate low-flow characteristics at ungaged sites from low streamflow analyses based on records at gaged sites. The use of the flow-routing method is suggested for areas where regression analysis proves unsuccessful, where low-flow characteristics have been defined at a significant number of sites, and where information about the basin characteristics has been thoroughly researched.

Low-flow frequency characteristics determined at 40 sites and measurements made during five synoptic runs in 1989-91 were used to develop a flow-routing method. Low-flow frequency characteristics and drainage areas were used to define river profiles for major streams within the Santa Fe River Basin. These river profiles serve as indicators of changes in a stream's low-flow characteristics with respect to change in drainage area. Unit low flows were also determined for each site where low-flow characteristics were determined. Areas of zero flow were defined for $Q_{7,2}$ and $Q_{7,10}$ conditions based on measurements made during synoptic runs and from low-flow frequency analyses.

The flow-routing method uses the drainage areas to interpolate low-flow values between or near gaged sites on the same stream. Low-flow values are transferred from a gaged site, either upstream or downstream, to the ungaged site. A step-by-step process for flow routing must be made when tributary or other inflow enter a stream. The strength of the flow-routing method is that the values at gaged sites reflect the overall basin characteristics in the vicinity of the gaged sites. However, the accuracy of low-flow estimates may be less in areas of decreasing and increasing flow if sufficient data are not available to assess changing hydraulic and hydrologic conditions.

INTRODUCTION

A low-flow frequency characteristic is an estimate of the discharge, averaged over a given consecutive-day period, which is not exceeded during a given interval of time (recurrence interval), on the average. Low-flow frequency characteristics are commonly used to evaluate waste-dilution potential and the water supply of streams, to establish minimum flows for regulatory programs, and for engineering design purposes. For example, estimates of the 7-day, 10-year low-flow frequency characteristic ($Q_{7,10}$) are used in formulating water-quality-based effluent limits (WQBELS) for waste discharges. Demands for low-flow information in many areas of Florida exceed the capabilities of existing data collection resources. To meet these demands, methods for estimating low-flow frequency characteristics at sites with little or no streamflow data (ungaged sites) are needed.

The most common means of quantifying low-flow information of streams is with statistical estimates of the magnitude and frequency of occurrence. Methods using regression analysis to relate low-flow frequency characteristics and selected basin characteristics could provide significant benefits for managers responsible for protecting surface-water quality and allocating surface-water supplies. Low-flow frequency characteristics with different consecutive-day averaging periods and recurrence intervals provide quantitative information that can be used in the management of a variety of additional water-quality and supply problems.

Background

Techniques for estimating low-flow frequency characteristics at ungaged sites in Florida streams have been addressed in two previous reports. Rabon (1971) used records through 1970 to develop regional low-flow relations in a regression analysis of low flow and basin characteristics. Two regions were analyzed separately: the Northwest Region, located west of and including part of Jefferson County; and the Peninsular Region, located east of and including part of Jefferson County. Equations were developed for 7-day low flows that have recurrence intervals of 2, 10, and 20 years. Standard errors of estimate for those equations are 83, 114, and 135 percent for the Northwest Region and 113, 419, and 562 percent for the Peninsular Region. Rabon concluded that low-flow characteristics at ungaged sites within most of the river basins in Florida could not be adequately estimated from his regional equations. However, he encouraged the collection of additional base-flow measurements as well as data on stream environment, particularly on basin characteristics that control low flows. These data would be used for advanced research for developing analytical methods that could provide more accurate estimates of low-flow characteristics.

Hammett (1985) presented low-flow frequency characteristics for 116 continuous-record and 108 partial-record and miscellaneous discharge-measurement stations for streams in west-central Florida. For streams unaffected by regulation or diversion, Hammett attempted to relate low-flow frequency characteristics to basin characteristics using multiple linear-regression analysis. Results from the analyses were considered unacceptable due to large standard errors of estimate (85 to more than 250 percent) and, more significantly, an apparent bias in the regression equations that resulted from compensating for zero flows.

In 1987, the U.S. Geological Survey (USGS) in cooperation with the Florida Department of Environmental Regulation (now the Florida Department of Environmental Protection), began a study to determine low-flow characteristics at all streamflow gaging stations and miscellaneous measurement sites within Florida where sufficient data were available. Rumenik and Grubbs (1996) presented low-flow characteristics for 211 continuous-record gaging stations and 242 partial-record stations and miscellaneous sites.

New techniques for analyzing low flow and additional years record have provided an opportunity to obtain more accurate estimates of low-flow characteristics than estimates presented in previous studies. This report presents methods for estimating 7- and 30-day low-flow statistics for ungaged sites in two areas in northern Florida based on the low-flow characteristics determined by Rumenik and Grubbs (1996).

Under an agreement with the Florida Department of Environmental Protection, the U.S. Geological Survey has established a computerized data base for base-flow measurements collected in Florida streams. Statistical programs that use this data base were applied to determine low-flow frequency estimates for partial-record stations throughout Florida (Rumenik and Grubbs, 1996). Estimates of the 7- and 30-day, 2- and 10-year low-flow recurrences ($Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$) have been defined where an adequate correlation exists with daily-record (index) stations. Low-flow characteristics for daily-record stations were determined by a mathematical procedure that fit a Pearson type III distribution to the logarithms of the low-flow values, or by a graphical technique in which the annual low-flow observations were ranked, assigned a recurrence interval, and plotted on normal probability graph paper. If the frequency characteristics obtained from the graphical and mathematical techniques were reasonably similar, then frequency characteristics from the Pearson type III distribution were reported; otherwise, frequency characteristics from the graphical technique were reported.

Two areas in northern Florida were selected to study the results of analyses in two diverse physiographic locations. The study areas selected are the Yellow, Blackwater, Escambia, and Perdido River Basins, a geomorphologically homogeneous area located in northwestern Florida; and the Santa Fe River Basin, a hydrologically complex area located in northeastern Florida (fig. 1). Distinctly different methods were used to estimate low-flow characteristics at ungaged sites in these study areas.

Purpose and Scope

This report describes the results of a study to develop methods for estimating low-flow frequency characteristics for periods of 7- and 30-consecutive days and for recurrence intervals of 2 and 10 years for ungaged sites in two areas of northern Florida. In the Yellow, Blackwater, Escambia and Perdido River Basins study area, multiple-linear regression techniques were used to develop equations that describe the relation between low flow and basin characteristics at 33 sites The method includes the use of a Geographical Information System (GIS), ARC/INFO, to identify and quantify basin characteristics. In the Santa Fe River Basin study area, a flow-routing method for estimating low-flow characteristics was used by relating the base-flow measurements collected at 40 sites to index stations, analyzing synoptic measurements, and defining points of zero flow along reaches of streams during designated low-flow events. The report discusses the methods applied for the two study areas and presents the results, the standard error of estimates (or accuracy of methods), and the limitations of the methods. The techniques described in this report for estimating low-flow characteristics were applied to sites on natural, unregulated streams.

Hydrologic Setting

Northern Florida is located within the Coastal Plain Physiographic Province, and its physiography can be described according to the three physiographic sections of the Coastal Plain in Florida: the Florida Section, the Gulf Coastal Plain Section, and the Atlantic Coastal Plain Section (Brooks, 1981; Fenneman, 1938; fig. 1). Most of northern Florida is within the Florida Section. Significant landscape features in this region include sequences of relict beach ridges and barrier islands; extensive marshes and swamps; and karstic features such as rolling limestone hills, sinkholes, and large magnitude springs. Many streams and rivers are sustained by significant ground-water contributions from the Floridan aquifer system which consists of a thick sequence of limestone that underlies at shallow depths much of the Florida Section.

The study area in northwestern Florida is located within the Gulf Coastal Plain Section of the Coastal Plain Province. This region is characterized by a hilly topography with great relief relative to peninsular Florida (Marsh, 1966). Many streams are deeply incised and derive much of their annual runoff from the sandy, surficial aquifer system that covers the region. The highest average annual rainfall (64 inches) and the lowest potential evaportranspiration (33 inches) occur in this part of Florida (Fernald and Patton, 1984). The average annual runoff is 25 to 40 inches. Monthly average flow is generally lowest in November and December.

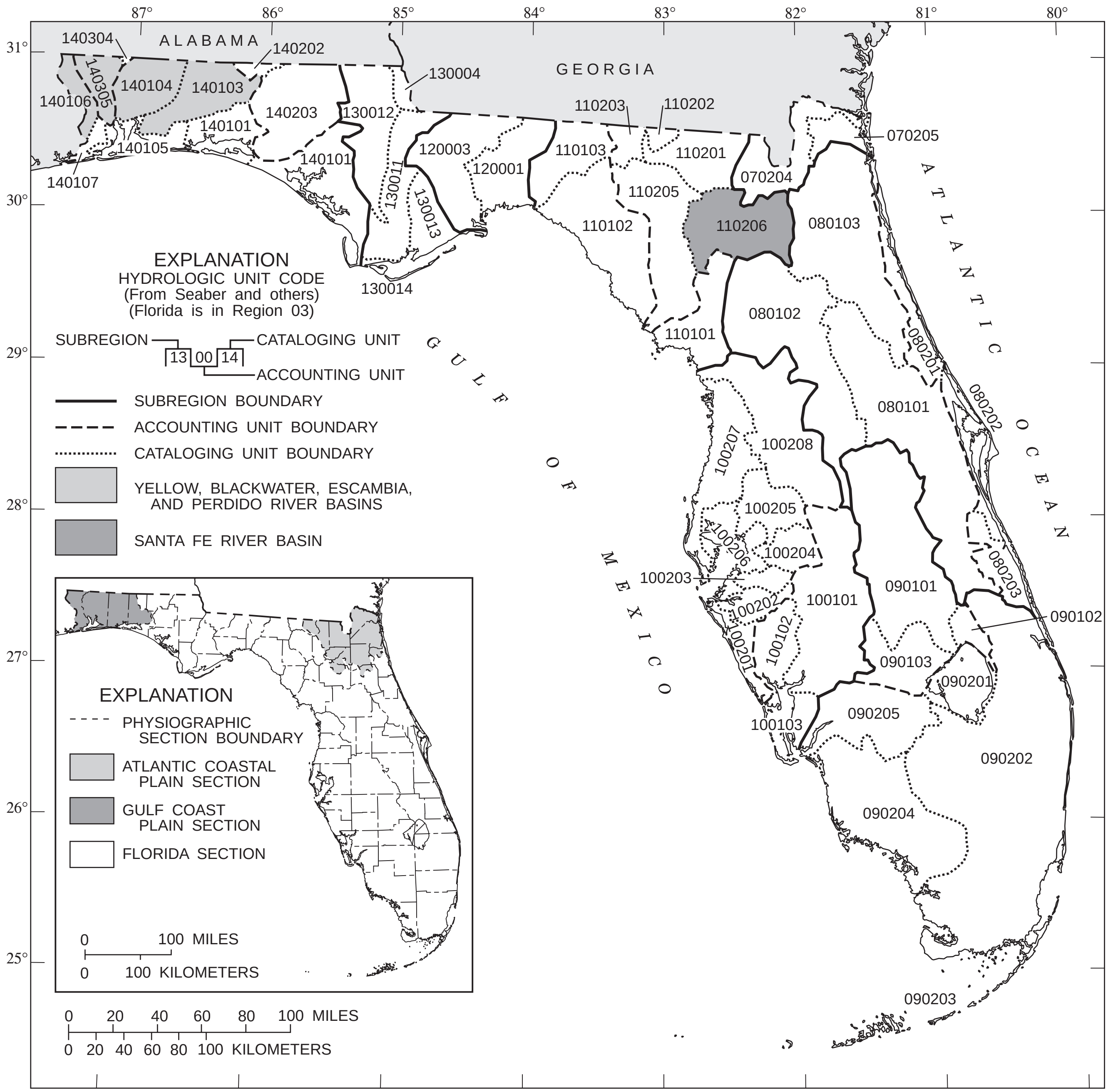

Figure 1. Study areas, hydrologic units, and physiographic sections in northern Florida.

The Yellow, Blackwater, Escambia, and Perdido Rivers are the principal streams within their respective basins that begin in southern Alabama and drain major parts of areas in Walton, Okaloosa, Santa Rosa, and Escambia Counties in Florida. These four river basins drain a total area of 7,383 square miles, of which 5,148 square miles (70 percent) is in Alabama and 2,235 square miles (30 percent) is in Florida. These basins provide inflow to coastal bay areas at and near Pensacola that drain to the Gulf of Mexico. The sand-and-gravel aquifer occurs at the surface in most of the area, except in northern Walton County where the upper Floridan aquifer crops out. The thickness of the sand-and-gravel aquifer ranges from less than 50 feet in southern Walton County to 700 feet in Escambia County (Cushman-Roisin, 1982).

In the study area in northeastern Florida, the Santa Fe River is a major tributary to the lower Suwannee River and drains an area of 1,384 square miles. Secondary tributary streams include the Ichetucknee and New Rivers and Olustee Creek. The Upper Floridan aquifer underlies the entire Santa Fe River Basin at the surface or at shallow depths. Rainfall in the Santa Fe River Basin averages about 54 inches; average annual runoff is 13 inches (not including spring inflow to the stream).

In the eastern part of the Santa Fe River Basin, the Upper Floridan aquifer is confined and overlain by a surficial sand aquifer. The surficial aquifer is recharged by local rainfall and, in some parts, by upward leakage through an underlying confining bed. The base flow of most of the streams in this area is supplied by the surficial aquifer. Numerous tributary streams supply small amounts of water to the Santa Fe River and the upper reaches of its principal tributary, the New River.

In most of the western part of the Santa Fe River Basin, confining bed sediments overlie the Upper Floridan aquifer except in the lower portion of the Santa Fe River. Discharge from water-yielding zones above the confining bed recharges the Upper Floridan aquifer. Primarily, the Floridan aquifer is recharged directly by rainfall in the lower portion of the Santa Fe River Basin (Hunn and Slack, 1983). Spring discharge from the Floridan aquifer augments the flow of the Santa Fe and Ichetucknee Rivers.

Low-Flow Characteristics of the Yellow, Blackwater, Escambia, and Perdido River Basins

Data Used in the Analysis

A Geographic Information System (GIS), ARC-INFO, was used to quantify basin characteristics that were used in regression equations to estimate $Q_{7,10}$ and $Q_{30,10}$ in the Yellow, Blackwater, Escambia, and Perdido River Basins. Several sources of digital data were used in this analysis. Elevation data were obtained from a digital elevation model, or DEM (U.S. Geological Survey, 1987), which consisted of a grid of elevation points spaced at approximately 30-meter intervals. Stream length data were obtained by selecting stream features from a digital hydrography coverage (U.S. Environmental Protection Agency, 1994), hereafter referred to as the RF3 coverage. Note that all stream reaches that were represented by double line stream segments (representing the right and left bank of a stream) were converted to a single line representation. Watershed boundaries were digitized from delineations made on USGS 7.5-minute topographic maps.

Development of Method for Estimating Low-Flow Characteristics

In northwestern Florida, a statistical technique known as regression analysis was used to develop equations for estimating low-flow frequency characteristics at ungaged sites. The equations were of the following form:

$$\hat{Q}_{N,T} = exp(\beta_0 + \beta_1 X)\gamma \qquad (1)$$

where $\hat{Q}_{N,T}$ is the estimate of the true value of the *N*-day, *T*-year low-flow frequency characteristic ($Q_{N,T}$); β_0 and β_1 are the slope and intercept of the equation, respectively; X is a basin characteristic (for example, the drainage area or stream density), γ is a nonparametric "unbiasing coefficient" (Helsel and Hirsch, 1992, p. 257), and $exp(x) = e^x$. Specific examples of these equations and their application are presented later in the report. These equations allow one to estimate the $Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$ by determining values of basin characteristics from digital GIS coverages or hardcopy maps and substituting these values into the appropriate equation. This section of the report describes how these equations were developed.

The first phase of equation development consisted of identifying basin characteristics that might account for the variability of low-flow characteristics in northwestern Florida. An example of such a basin characteristic is the area of the basin (often called the drainage area of the basin). Although drainage area is typically the most important basin characteristic for estimating low-flow characteristics in ungaged basins, previous studies have often shown that other basin characteristics may be important at improving the accuracy of these estimates. These basin characteristics are typically related to surficial geology because differences in low-flow frequency characteristics in unregulated basins are largely due to the differences in ground-water discharge to streams. An example of such a basin characteristic is the percentage of drainage area underlain by a given formation. However, geologically-derived basin characteristics were not used because the surficial geology changes very little over the study area. Geomorphic descriptions of basins may also be useful predictors of low-flow characteristics because they often describe factors that affect ground-water discharge to streams. Examples of this type of basin characteristic include stream incisement and basin relief. The former characteristic accounts for depth to which a stream penetrates an aquifer and the latter is often correlated with water-table slope and recharge.

Several hydrologically-based basin characteristics were derived from geomorphic basin descriptions and identified as possible predictors of low-flow characteristics. These characteristics were developed from two simple conceptual models of ground-water discharge to streams. The first of these models is based on Darcy's law (Freeze and Cherry, 1979, p. 15) for one-dimensional ground-water flow:

$$q = -Kb\frac{(h_2 - h_1)}{L} \qquad (2)$$

where q is ground-water discharge per unit stream length (from one side of the stream), K is hydraulic conductivity of a porous medium (such as an aquifer), b is the aquifer thickness, h_1 and h_2 are hydraulic heads at the beginning and end, respectively, of a ground-water flow path of length L. An application of this equation to a stream receiving ground-water discharge is depicted in figure 2. In this application, h_1 is measured at some point "upgradient" from the stream, such as under a basin boundary, h_2 is measured at the stream-aquifer interface, and L is measured as the distance from the basin boundary to the stream-aquifer interface.

The second model is very similar to the Darcy-based model, but uses the Dupuit equation of ground-water flow (Fetter, 1988, p. 143):

$$q = -\frac{K}{2L}({h^2}_2 - h_1^2) \qquad (3)$$

where q is ground-water discharge per unit of stream length. The Darcy model can be used to represent steady ground-water flow from a confined aquifer, and the Dupuit model is used to represent steady ground-water flow from an unconfined aquifer. In the example shown in figure 2, Dupuit’s equation can be derived from Darcy’s law by substituting the water-table height for aquifer thickness. The resulting equation allows for the increase in

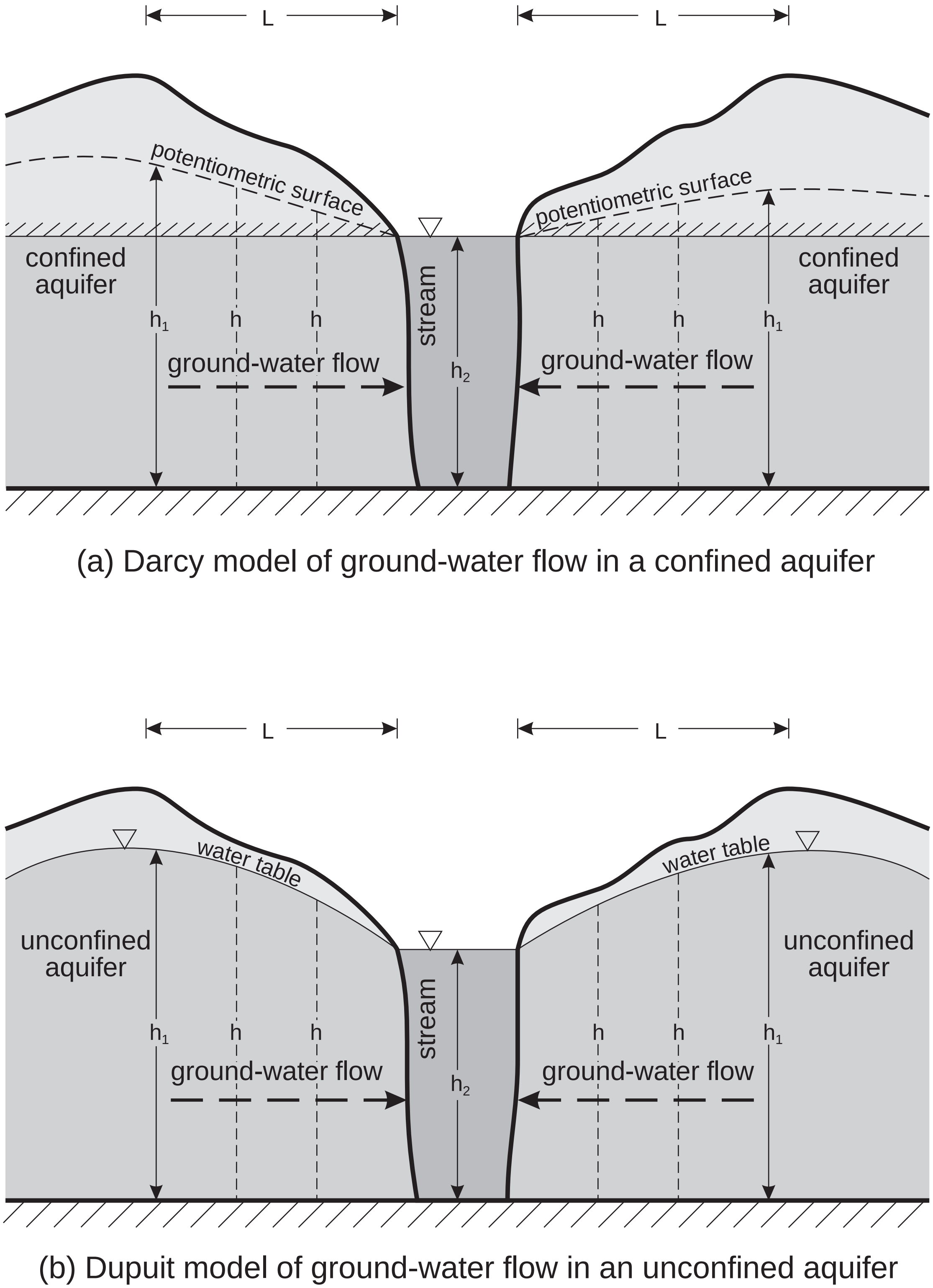

Figure 2. Darcy (A) and Dupuit (B) models of ground-water flow.

water table-slope that occurs as *h* decreases (due to decreasing water table height) along the flow path. Note that, to obtain total ground-water discharge, equations 2 and 3 must be applied to both sides of a stream, and this result then integrated over the entire length of the stream to compute total streamflow, *Q*. To approximate *Q*, an average value of the right side of equations 2 or 3 could be computed, multiplied by two, and finally multiplied by total stream length ($Q = 2qS_l$, where S_l is total stream length).

Selection of an appropriate model (Darcy or Dupuit) is complicated by the complex nature of the sand-and-gravel aquifer, which is the source of ground water to streams within the Yellow, Blackwater, and Escambia River Basins. Although ground-water flow is generally under unconfined conditions, limonite (hardpan) and clay layers which are interbedded within the more permeable sand and gravel deposits may create conditions of locally confined ground-water flow, as well as perched water tables. Many of the larger streams also receive ground water from a deeper permeable zone of the sand-and-gravel aquifer. Ground-water flow in this deeper zone may be confined by a less permeable sand-and-clay unit, which separates the deeper permeable zone from the upper (surficial) permeable zone. Because of the complex nature of ground-water flow within the sand-and-gravel aquifer, both the Darcy and Dupuit models were used to develop variables that might account for the variability of low flow.

As mentioned previously, the Darcy- and Dupuit-based measures of *Q* (*q* from equations 2 or 3 multiplied by twice the total stream length) were the basis for several hydrologically-based explanatory variables. *Q* was not used directly as an explanatory variable because some of the terms in equations 2 and 3 are difficult to quantify. Instead, explanatory variables were derived from equations 2 and 3 by eliminating some of the terms in these equations, and by using geomorphic or topographic variables as "surrogates" for the remaining terms. For example, hydraulic conductivity (*K*) was not used in the determination of explanatory variables because few measurements of *K* exist and the regional surficial geology in northwestern Florida is fairly uniform (indicating that basin to basin variations in *K* may not be significant enough to explain much of the variability of low-flow characteristics). A representative value of aquifer thickness was also not used in the determination of the hydrologically-based explanatory variables because streams in the study area do not fully penetrate the sand-and-gravel aquifer. As a result, these streams may not capture all of the ground-water discharge from the basin. Under these conditions, the average thickness of that part of the aquifer that discharges ground water to streams within a given basin (‘effective’ aquifer thickness) should be a suitable substitute for total aquifer thickness. However data describing the effective aquifer thickness are limited. For this reason, effective aquifer thickness was not explicitly included in the calculation of *q* (and therefore *Q*). However, because effective aquifer thickness is correlated with stream length (which is being used to estimate *L* and appears in the numerator of the equation for calculating *Q* -see below), effective aquifer thickness is implicitly included in the calculation of *Q*.

The remaining terms in equations 2 and 3 (L, h_1, and h_2) were included in the determination of hydrologically-based explanatory variables, but values for these terms were estimated by using geomorphic or topographic measures. For example, ground-water flow path length (L) was estimated as half of the inverse of stream density (total stream length divided by drainage area). Use of this estimate of L can be understood by imagining a hypothetical rectangular basin drained by one stream that stretches the entire length of the basin and lies equidistant from the lateral basin divides (basin length equals stream length, and the stream bisects the basin lengthwise). The area of such a basin is equal to the stream length multiplied by the basin width (or stream length multiplied by twice the average ground-water flow-path length, L). Therefore, L in such a basin is equal to one half the inverse of stream density. Drainage density was determined for individual basins by calculating the total stream length, S_l, using a GIS and the RF3 hydrographic data and dividing by the drainage area. Land surface elevation data were used as a surrogate variable for h_1 because of limited water table data in the study area and the generally high correlation between h_1 and land surface elevation. Various measures of land surface elevation were tested as surrogates for h_1: mean elevation of basin divide, maximum elevation of basin divide, and mean basin elevation. Mean basin elevation was tested because it should lead to a better estimate of ground-water discharge when the basin relief (as measured by the change in elevation from basin divide to stream) is steep. Also, mean basin elevation better reflects the average thickness of that part of the aquifer which contributes water to streams within a given basin. Three measures of h_2 were evaluated using hydrographic and topographic data: minimum stream elevation, mean stream elevation, and minimum elevation along the drainage basin divide. Stream elevations were determined in a two step procedure. First, a GIS line coverage of the streams within a basin (described above) was converted to a raster representation or grid (in which grid cells would have a value of one if traversed by a stream segment, and zero otherwise). Then, a stream elevation grid was created by assigning elevation values from the DEM grid to grid cells that were traversed by a stream. Note that a similar procedure was used with the DEM grid and GIS line and polygon coverages of drainage basin divides to calculate the three alternative measures of h_1.

Given the preceding discussion regarding the elimination of K and b from equation 2 and 3, the use of geomorphic and topographic measures for L, h_1, and h_2, and the conversion of q to Q ($Q = 2qS_l$) , the following equations were used to calculate Q:

Darcy model:

$$Q_{Darcy} = -2\left[\frac{(h_2 - h_1)}{L}\right]S_l = -4(h_2 - h_1)S_\rho S_l = -4(h_2 - h_1)\frac{S_l^{\ 2}}{A_d} \qquad (4)$$

Dupuit model:

$$Q_{Dupuit} = -\frac{2(h_2^2 - h_1^2)}{2L}S_l = -\frac{2}{2}(h_2^2 - h_1^2)2S_\rho S_l = -2(h_2^2 - h_1^2)S_\rho S_l = -2(h_2^2 - h_1^2)\frac{S_l^{\ 2}}{A_d} \qquad (5)$$

where S_ρ is stream density, S_l is total stream length within the basin, and A_d is the drainage area of the basin. As previously mentioned three different measures of h_1 and h_2 were used to calculate Q, which lead to 9 possible combinations of h_1 and h_2, and 9 different measures of Q_{Darcy} and Q_{Dupuit} .

Each of these 9 measures of Q_{Darcy} and Q_{Dupuit} (18 different measures of Q) were tested as possible predictors of low-flow frequency characteristics. Eighteen additional measures of Q were also tested in which Q_{Darcy} or Q_{Dupuit} were computed by multiplying the average head gradient (change in head per unit L) by drainage area, instead of multiplying the gradient by the total stream length. This leads to following alternative measures of Q_{Darcy} and Q_{Dupuit} :

$$Q_{Darcy, A_d} = -2\left[\frac{(h_2 - h_1)}{L}\right]A_d = -4(h_2 - h_1)S_p A_d = -4(h_2 - h_1)(S_l / A_d)A_d = -4(h_2 - h_1)S_l \quad (6)$$

$$Q_{Dupuit, A_d} = -\frac{2(h_2^2 - h_1^2)}{2L}A_d = -\frac{2}{2}(h_2^2 - h_1^2)2S_p A_d = -2(h_2^2 - h_1^2)(S_l / A_d)A_d = -2(h_2^2 - h_1^2)S_l \quad (7)$$

In addition, drainage area, total stream length, drainage density, and 18 measures of basin relief and gradient were tested (which corresponded to the 9 possible combinations of h_1 and h_2 in the Darcy or Dupuit models). Regression models with more than one basin characteristic were not evaluated in the regression analysis because of the small sample size available (only 20 to 37 low-flow frequency characteristics were available from the study area). As a result 75 different single basin-characteristic models were evaluated. All of the models were first evaluated by visually inspecting scatter plots of the data, which show the relation between frequency characteristics and basin characteristics. Two statistical criteria were then used to evaluate ordinary least squares (OLS) regression models of these relations: the mean square error (Helsel and Hirsch, 1992, p. 227), and the PRESS statistic (Helsel and Hirsch, 1992, p. 248). Both criteria consistently indicated the same ‘best fit’ regression model. Finally, residual plots (difference between the observed and model-predicted values of the frequency characteristic plotted against model-predicted values) were examined to evaluate whether model errors were approximately constant regardless of the magnitude of the basin characteristic used in the model. The residual plots were also used as a final check on the assumption that the relation between the frequency and basin characteristic is linear.

Inspection of the scatter and residual plots generally indicated nonlinear relations between the low-flow frequency characteristics and basin characteristics. The residual plots also indicated that the model errors were also nonconstant. Both problems (nonlinearity and nonconstant variance) were resolved by using the natural logarithms of the low-flow frequency characteristics and basin characteristics in the regression models.

Regression models that used Q_{Darcy, A_d} as the explanatory variable resulted in the best fit equations and are given as follows:

$$\hat{Q}_{7,2} = exp[3.742 + 0.866\, ln(Q_{Darcy, A_d})]1.168 \quad (8)$$

$$\hat{Q}_{7,10} = exp[3.634 + 0.733\, ln(Q_{Darcy, A_d})]1.128 \quad (9)$$

$$\hat{Q}_{30,2} = exp[4.030 + 0.805\, ln(Q_{Darcy, A_d})]1.117 \quad (10)$$

$$\hat{Q}_{30,10} = exp[3.837 + 0.738\, ln(Q_{Darcy, A_d})]1.090 \quad (11)$$

where Q_{Darcy, A_d} is the Darcy-based estimate of the basin characteristic, Q_{Darcy}, which was computed by multiplying the average basin gradient by the basin drainage area, instead of by the total stream length within the basin (see above discussion). The mean elevation within the basin and the mean stream elevation measures of h_1 and h_2, respectively, were used to calculate Q_{Darcy, A_d} and resulted in the best fit among the other measures of these variables. It should be noted that the Dupuit-based variable Q_{Dupuit, A_d} (using the mean elevation within the basin and the mean stream elevation measures of h_1 and h_2, respectively) performed nearly as well as Q_{Darcy, A_d}. Standard errors for models employing this measure of Q_{Dupuit, A_d} were 67.4, 63.9, 54.2, and 47.5 for $Q_{7, 2}$, $Q_{7, 10}$, $Q_{30, 2}$, and $Q_{30, 10}$ (as compared to 64.7, 57.6, 51.2, and 44.4, respectively, for the models based on Q_{Darcy, A_d}).

Less accurate regression models were also fit using the basin drainage area as the explanatory variable. Although less accurate than equations 8-11, the drainage area models are useful because they do not require determinations of mean basin and stream elevations, and total stream lengths. The drainage area models are given in the following equations:

$$\hat{Q}_{7, 2} = exp[0.508 + 0.825\,ln(A_d)]1.232 \tag{12}$$

$$\hat{Q}_{7, 10} = exp[0.818 + 0.723\,ln(A_d)]1.171 \tag{13}$$

$$\hat{Q}_{30, 2} = exp[1.043 + 0.770\,ln(A_d)]1.153 \tag{14}$$

$$\hat{Q}_{30, 10} = exp[1.051 + 0.716\,ln(A_d)]1.134 \tag{15}$$

Information regarding the standard error, number and type of sites, and minimum and maximum values of Q_{Darcy, A_d} and drainage area for each of the above equations is shown in table 1.

Table 1. Standard error of prediction, number and type of sites, and range of explanatory variable values used in the development of regionalization equations in the Yellow, Blackwater, Escambia, and Perdido River Basins

[--, no drainage area]

Low-flow quantile	Explanatory variable	Standard error[1], in percent	Number of partial record sites used	Number of continuous record sites used	Drainage area, in square miles Min	Drainage area, in square miles Max	Q_{Darcy, A_d}, in square miles Min	Q_{Darcy, A_d}, in square miles Max
$Q_{7, 2}$	Q_{Darcy, A_d}	64.7	21	10	--	--	0.02824	26.507
$Q_{7, 2}$	A_d	74.3	21	12	1.45	4150	--	--
$Q_{7, 10}$	Q_{Darcy, A_d}	57.6	14	10	--	--	0.2050	26.507
$Q_{7, 10}$	A_d	62.5	14	12	7.51	4150	--	--
$Q_{30, 2}$	Q_{Darcy, A_d}	51.2	15	10	--	--	0.2050	26.507
$Q_{30, 2}$	A_d	53.6	15	12	7.51	4150	--	--
$Q_{30, 10}$	Q_{Darcy, A_d}	44.4	10	10	--	--	0.2050	26.507
$Q_{30, 10}$	A_d	51.3	10	12	7.51	4150	--	--

[1]Standard error is calculated as $100\sqrt{\exp[(Mean\ Square\ Error)^2] - 1}$

Ninety-five percent confidence intervals for equations 8 through 15 can be computed using the following equation and the data in table 2:

$$exp\left\{ln(\hat{Q}_{N,T}) - t_{\alpha/2, n-2}\sqrt{MS_E\left[1 + \frac{1}{n} + \frac{(ln x_o - \overline{ln x})^2}{S_{lnx\,lnx}}\right]}\right\} \le Q_{N,T} \le$$

$$exp\left\{ln(\hat{Q}_{N,T}) + t_{\alpha/2, n-2}\sqrt{MS_E\left[1 + \frac{1}{n} + \frac{(ln x_o - \overline{ln x})^2}{S_{lnx\,lnx}}\right]}\right\} \quad (16)$$

where $\hat{Q}_{N,T}$ is the N-day, T-year low-flow quantile estimate obtained from equations 8-15 $t_{\alpha/2, n-2}$ is the critical value of the student's t test statistic at an $\alpha/2$ confidence level and sample size of *n* (for a 95-percent confidence level $\alpha = 0.05$); MS_E is the mean square error of the regression model; x_o is the value of the explanatory variable of the corresponding regression equation (either Q_{Darcy, A_d} or A_d) at the ungaged site, $\overline{lnx}$ and $S_{lnx\,lnx}$ are the mean value and corrected sum of squares, respectively, of the log-transformed values of the explanatory variable at the sites used to fit equations 8-15. Step-by-step examples of calculating confidence intervals for quantile estimates computed from equations 8-15 are presented in the next section of this report. Note that equation 16 and table 2 can be used to compute confidence intervals for any desired level of confidence (α) by using a different value of $t_{\alpha/2,\, n-2}$ in equation 16.

Table 2. Data necessary for computing 95-percent confidence intervals for quantile estimates from regionalization equations in the Yellow, Blackwater, Escambia, and Perdido River Basins

Low-flow quantile	Explanatory variable	Number of stations, n	$t_{0.05/2,\, n-2}$	MS_E	Mean value of explanatory variable, $\overline{ln(x)}$	Corrected sum of squares, $S_{lnx\,lnx}$
$Q_{7,\,2}$	$Q_{Darcy,\, A_d}$	31	2.045	0.350	0.350	60.244
$Q_{7,\,2}$	A_d	33	2.040	0.439	4.527	90.840
$Q_{7,\,10}$	$Q_{Darcy,\, A_d}$	24	2.074	0.287	0.639	36.410
$Q_{7,\,10}$	A_d	26	2.064	0.330	4.843	63.048
$Q_{30,\,2}$	$Q_{Darcy,\, A_d}$	25	2.069	0.233	0.536	40.214
$Q_{30,\,2}$	A_d	27	2.052	0.253	4.727	70.250
$Q_{30,\,10}$	$Q_{Ddarcy,\, A_d}$	20	2.101	0.180	0.611	36.179
$Q_{30,\,10}$	A_d	22	2.086	0.234	4.869	62.847

Application of Method

Estimates of low-flow quantiles at ungaged sites in the Yellow, Blackwater, Escambia, and Perdido River basins can be made with equations 8-15, and a 95-percent confidence interval can be computed using equation 16 and data from table 2. A step-by-step example of estimating low-flow quantiles and computing 95-percent confidence intervals for these quantiles is presented in this section. The limitations of the equations 8-16 are also discussed.

A site located on Sweetwater Creek near Munson, Florida (site number 02370230) is used in the example. Estimates of $Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$ low-flow quantiles, as well as confidence limits are computed in the example. Two alternative sets of quantiles are estimated: one set uses the Darcy-based explanatory variable, $Q_{Darcy,\, A_d}$, and the other set will use drainage area as the explanatory variable. Estimation of low-flow quantiles using drainage area (equations 12-15) may be preferable if the analyst does not have the time or computer resources necessary to compute a value for $Q_{Darcy,\, A_d}$.

The first step in calculating estimates of $Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$ is to determine values of the explanatory variable being employed. Use of equations 8-11 requires the determination of $Q_{Darcy,\, A_d}$, which in turn requires the determination of values of S_l, h_1, and h_2. Drainage area (A_d) is typically determined by delineating the watershed boundary for the basin in question on U.S.G.S. 7.5-minute topographic maps and computing the area within the delineated boundary either by planimeter or with a GIS (after digitizing the boundary). A drainage area value is the only determination required if equations 12-15 are being used. The total stream length, S_l, may be similarly determined using a planimeter and hardcopy maps, or with a GIS and digital streams coverage (the 'single-line' streams coverage used in this study may be obtained from the USGS office in Tallahassee, Florida). If a GIS is used, the digitized watershed boundary must be used to 'clip out' the streams within the basin, before computing total stream length. Mean basin elevation (h_1) can be estimated by several methods. If a GIS is not available, h_1 may be determined either by visual inspection of a topographic map or, preferably, by using a planimeter to compute the total length of each elevation contour within the basin and computing a weighted average elevation (sum the products of the value of each contour line and the length of each line, and divide this sum by the total length of all contour lines in the basin). If a suitable GIS is available, a mean basin elevation can be computed from a DEM that has been clipped with the watershed boundary coverage. Mean stream elevation (h_2) can be computed using one of two methods. If a GIS is not available, h_2 can be computed by noting the elevation value at every intersection of a stream and an elevation contour, and computing the mean of all of these values. If a suitable GIS is available, h_2 can be computed by intersecting a digital streams coverage and a DEM. Once values for S_l, h_1, and h_2 are determined, Q_{Darcy, A_d} is calculated as $-4(h_2 - h_1)S_l$.

Estimates of $Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$ and can now be obtained by substituting the appropriate values of Q_{Darcy, A_d} into equations 8-11 or, alternatively, values of A_d into equations 12-15. The following values of A_d, S_l, h_1, and h_2 were determined for our example basin, Sweetwater Creek near Munson:

A_d = 45.0 square miles

S_l = 52.8 miles

h_1 = 220.5 feet

h_2 = 205.9 feet.

The values of S_l, h_1, and h_2 yield the following value of Q_{Darcy, A_d} for the Sweetwater Creek example:

$$Q_{darcy, A_d} = -4(205.9\ feet\ -220.5\ feet)\left(\frac{1\ mile}{5280\ feet}\right)52.8\ miles = 0.5840\ square\ mile$$

This value of Q_{Darcy, A_d} is substituted into equations 8-11 to obtain estimates of $Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$:

$$\hat{Q}_{7,2} = exp[3.742 + 0.866\ ln\ (0.584)]1.168 = 30.9\ ft^3/s \tag{17}$$

$$\hat{Q}_{7,10} = exp[3.634 + 0.733\,ln(0.584)]1.128 = 28.8\ ft^3/s \tag{18}$$

$$\hat{Q}_{30,\,2} \;=\; exp[4.030 + 0.805\,ln(0.584)]1.117 \;=\; 40.8\ ft^3/s \qquad (19)$$

$$\hat{Q}_{30,\,10} \;=\; exp[3.837 + 0.738\ln(0.584)]1.090 \;=\; 34.0\ ft^3/s \quad . \qquad (20)$$

If drainage-area based estimates of $Q_{7,\,2}$, $Q_{7,\,10}$, $Q_{30,\,2}$, and $Q_{30,\,10}$ are desired then A_d is substituted into equations 12-15 to yield the following:

$$\hat{Q}_{7,\,2} \;=\; exp[0.508 + 0.825\,ln(45.0)]1.232 \;=\; 47.3\ ft^3/s \qquad (21)$$

$$\hat{Q}_{7,\,10} \;=\; exp[0.818 + 0.723\,ln(45.0)]1.171 \;=\; 41.6\ ft^3/s \qquad (22)$$

$$\hat{Q}_{30,\,2} \;=\; exp[1.043 + 0.770\ ln(45.0)]1.153 \;=\; 61.3\ ft^3/s \qquad (23)$$

$$\hat{Q}_{30,\,10} \;=\; exp[1.051 + 0.716\ \ln(45.0)]1.134 \;=\; 49.5\ ft^3/s \quad . \qquad (24)$$

Once estimates of low-flow quantiles have been computed, a 95-percent prediction interval can be determined to assess the accuracy of these quantile estimates. This is accomplished by substituting the low-flow quantile values from equations 8-15 and the appropriate values from table 2 into equation 16. To simplify the presentation of the Sweetwater Creek example, equation 16 will be reexpressed as:

$$exp[ln(\hat{Q}_{N,\,T}) - \gamma] \le Q_{N,\,T} \le \ exp[ln(\hat{Q}_{N,\,T}) + \gamma]$$

where

$$\gamma \;=\; t_{\alpha/2,\,n-2}\sqrt{MS_E\left[1 + \frac{l}{n} + \frac{(lnx_o - \overline{lnx})^2}{S_{lnx\,lnx}}\right]} \quad . \qquad (25)$$

The ninety-five percent confidence intervals can now be constructed by first computing a value for γ and substituting the result into equation 26. For the Darcy-based estimates of $Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$, the values of γ are as follows:

For $Q_{7,2}$, $\gamma = 2.045\sqrt{0.350\left[1 + \frac{1}{31} + \frac{(ln(0.584) - 0.350)^2}{60.244}\right]} = 1.237$ and

$$exp[ln(30.9) - 1.237] = 9.0\ ft^3/s \le \hat{Q}_{7,2} \le exp[ln(30.9) + 1.237] = 106\ ft^3/s \quad .$$

For $Q_{7,10}$, $\gamma = 2.074\sqrt{0.287\left[1 + \frac{1}{24} + \frac{(ln(0.584) - 0.639)^2}{36.410}\right]} = 1.154$ and

$$exp[ln(28.8) - 1.154] = 9.1\ ft^3/s \le \hat{Q}_{7,10} \le exp[ln(28.8) + 1.154] = 91.3\ ft^3/s \quad .$$

For $Q_{30,2}$, $\gamma = 2.069\sqrt{0.233\left[1 + \frac{1}{25} + \frac{(ln(0.584) - 0.536)^2}{40.214}\right]} = 1.032$ and

$$exp[ln(40.8) - 1.032] = 14.5\ ft^3/s \le \hat{Q}_{30,2} \le exp[ln(40.8) + 1.032] = 114\ ft^3/s \quad .$$

For $Q_{30,10}$, $\gamma = 2.101\sqrt{0.180\left[1 + \frac{1}{20} + \frac{(ln(0.584) - 0.611)^2}{36.179}\right]} = 0.929$ and

$$exp[ln(34.0) - 0.929] = 13.4\ ft^3/s \le \hat{Q}_{30,10} \le exp[ln(34.0) + 0.929] = 86.1\ ft^3/s \quad .$$

The 95-percent confidence intervals can similarly be computed for drainage-area based estimates of $Q_{7,2}$ $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$ at the Sweetwater Creek site:

For $Q_{7,2}$, $\gamma = 2.040\sqrt{0.439\left[1 + \frac{1}{33} + \frac{(ln(45.0) - 4.527)^2}{90.840}\right]} = 1.376$ and

$$exp[ln(47.3) - 1.376] = 11.9\ ft^3/s \le \hat{Q}_{7,2} \le exp[ln(47.3) + 1.376] = 187 ft^3/s \quad .$$

For $Q_{7,10}$, $\gamma = 2.064\sqrt{0.330\left[1 + \frac{1}{26} + \frac{(ln(45.0) - 4.843)^2}{63.048}\right]} = 1.218$ and

$$exp[ln(41.6) - 1.218] = 12.3\ ft^3/s \le \hat{Q}_{7,10} \le exp[ln(41.6) + 1.218] = 141\ ft^3/s \quad .$$

For $Q_{30,2}$, $\gamma = 2.052\sqrt{0.253\left[1 + \frac{1}{27} + \frac{(ln(45.0) - 4.727)^2}{70.250}\right]} = 1.057$ and

$$exp[ln(61.3) - 1.057] = 21.3\ ft^3/s \leq \hat{Q}_{30,\,2} \leq exp[ln(61.3) + 1.057] = 176\ ft^3/s$$.

For $Q_{30,\,10}$, $\gamma = 2.086\sqrt{0.234\left[1 + \frac{1}{22} + \frac{(ln(45.0) - 4.869)^2}{62.847}\right]} = 1.040$ and

$$exp[ln(49.5) - 1.040] = 17.5\ ft^3/s \leq \hat{Q}_{30,\,10} \leq exp[ln(49.5) + 1.040] = 140\ ft^3/s$$.

There are several limitations to the application of any of the above equations. Before computing quantile estimates, the explanatory variable value must be checked to make sure that is does not lie outside of the range of Q_{Darcy, A_d} or A_d values used to fit the regression models represented by equations 8-15. Regression models are intended to be used as interpolation equations over the range of data used to fit the models, and may not be valid for data outside of this range (Montgomery and Peck, 1982, p. 34). For the Sweetwater Creek example, the value of Q_{Darcy, A_d} is 0.5840 square mile and an A_d of 45 square miles. Both of these values are within the ranges of values used to fit regression equations 8-15 (these ranges are shown in table 1). Therefore, the above estimates of $Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10}$ are valid because none of these values required extrapolating beyond the ranges of the data used to fit equations 8-15.

The reader should also be extremely cautious when applying equations 8-15 outside of the Yellow, Blackwater, Escambia, and Perdido River Basins. The chief reason for this limitation is that these equations are dependent on the hydrogeologic, and climatic characteristics of this region. Neither of these factors is accounted for by the explanatory variables, Q_{Darcy, A_d} and A_d . Therefore, large errors could result if the hydrogeology and climate of an ungaged basin are significantly different than that found in the basins used to fit equations 8-15.

Low-Flow Characteristics of the Santa Fe River Basin

Data Used in the Analysis

As a means of developing a flow-routing method for estimating low-flow values at ungaged sites, base-flow measurement data from five data-collection efforts were used to assess the variation of low-flow conditions within a few-day period over the entire basin. The collection of these additional base-flow measurements at new and existing stream sites improved the accuracy and coverage of low-flow frequency estimates available for analysis. Synoptic-measurement runs 1 and 2 were made in May and June 1989; runs 3 and 4, August and September 1990; and run 5, November 1991. Also considered in the analysis was an extensive coverage of measurements made during May 24 and 25, 1977 (Hunn and Slack, 1983).

Table 3 presents low-flow frequency estimates determined at 20 sites in a previous study (Rumenik and Grubbs, 1996), and 20 additional sites, based on data collected during synoptic-measurement runs. These measurements were used in the application to develop a flow-routing method for estimating low flows within the basin. Figure 3 shows the location of sites in the Santa Fe River Basin that were used in the analyses to develop a method for estimating low-flow characteristics. The length of record for data used in the analysis for low-flow characteristics at each station was from the beginning of record to 1994.

Table 3. Low-flow frequency data and unit low flow for data-collection sites in the Santa Fe River Basin

Map no.	Site ID	Station name	Drainage area, (DA), in mi^2	$Q_{7,2}$		$Q_{7,10}$		$Q_{30,2}$		$Q_{30,10}$	
				ft^3/s	ft^3/s / DA	ft^3/s	ft^3/s / DA	ft^3/s	ft^3/s / DA	ft^3/s	ft^3/s / DA
1*	02319800	SUWANNEE RIVER AT DOWLING PARK, FL	7,190.0	1,800	0.250	1,150	0.160	1,950	271	11200	0.167
2*	02320000	SUWANNEE RIVER AT LAURAVILLE, FL	7,330.0	2,170	0.296	1,460	0.199	2,270	0.310	1470	0.201
3*	02320500	SUWANNEE RIVER AT BRANFORD, FL	7,880.0	2,580	0.327	1,810	0.230	2,680	0.340	1840	0.234
4	02320700	SANTA FE RIVER NR GRAHAM, FL	94.9	0.54	006	0.08.	001	1.1	0.012	0.16	0.002
5	02320732	ALLIGATOR CREEK AT STARKE, FL	19.4	2.9	0.149	0.8	0.041	5.5	0.284	1.8	0.093
6	02320800	SAMPSON RIVER AT SAMPSON, FL	59.7	3.0	0.050	0.37	0.006	6.5	0.109	0.80	0.013
7	02320815	SAMPSON RIVER AT GRAHAM, FL	74.3	(>0)	--	(>0)	--	--	--	--	--
8	02320849	SANTA FE RIVER AT BROOKER, FL	245.0	10.	0.041	0.9	0.004	--	--	--	--
9	02320870	ROCKY CREEK NR LA CROSSE, FL	22.6	(0.0)	0.000	(0.0)	0.000	--	--	--	--
10	300612082094000	NEW RIVER AT SR 125, NR RAIFORD, FL	79.0	(0.0)	0.000	(0.0)	0.000	--	--	--	--
11	02320898	ALLIGATOR CREEK NR LAWTEY, FL	28.0	(0.0)	0.000	(0.0)	0.000	--	--	--	--
12	02320900	NEW RIVER NR RAIFORD, FL	93.3	0.34	0.004	0.05	0.001	0.80	0.009	0.17	0.002
13	02320950	WATER OAK CREEK NR STARKE, FL	20.7	0.0	0.000	0.0	0.000	0.01	0.000	0.0	0.000
14	02320960	WATER OAK CREEK NR LAWTEY, FL	39.0	0.1	0.003	0.02	0.001	0.2	0.005	0.05	0.001
15	300212082131900	NEW RIVER AT SH 229, NR RAIFORD, FL	135.0	(>0)	--	(>0)	--	--	--	--	--
16	02321000	NEW RIVER NR LAKE BUTLER, FL	193.0	2.1	0.011	0.68	0.004	3.5	0.018	1.4	0.007
17	02321200	RICHARD CREEK NR LAKE BUTLER, FL	13.9	0.0	0.000	0.0	0.000	--	--	--	--
18	295700082204300	NEW RIVER NR BROOKER, FL	241.0	(4.9)	0.020	(1.5)	0.006	--	--	--	--
19	295535082244000	NEW RIVER NR WORTHINGTON SPRINGS, FL	276.0	3.8	0.014	1.1	0.004	6.7	0.024	2.5	0.009
20	02321500	SANTA FE RIVER AT WORTHINGTON SPRINGS, FL	575.0	13	0.028	3.2	0.006	20	0.035	6.0	0.010
21	295633082302500	SANTA FE RIVER NR BLAND, FL	611.0	--	--	0.0	0.000	--	--	--	--
22	02321600	OLUSTEE CREEK NR LULU, FL	49.1	0.10	0.002	0.0	0.000	0.28	0.006	0.05	0.001
23	300328082315800	OLUSTEE CREEK AT S.H. 240, NR PROVIDENCE, FL	64.9	0.0	0.000	0.0	0.000	--	--	--	--
24	02321700	SWIFT CREEK NR LAKE BUTLER, FL	46.0	0.0	0.000	0.0	0.000	0.11	0.002	0.02	0.000
25	300204082313100	SWIFT CREEK NR PROVIDENCE, FL	78.7	(0.0)	0.000	(0.0)	0.000	--	--	--	--
26	02321800	OLUSTEE CREEK NR PROVIDENCE, FL	163.0	0.0	0.000	0.0	0.000	--	--	--	--
27	02321894	OLUSTEE CREEK TRIBUTARY NR PROVIDENCE, FL	3.3	(>0,1)	(>0,<1)	--	(>0,<1)	--	--	--	--
28	295701082315000	OLUSTEE CREEK AT SR 18, NR PROVIDENCE, FL	185.0	0.0	0.0	0.000	0.0	0.000	--	--	--
29	02321898	SANTA FE RIVER AT O'LENO STATE PARK, FL	820.0	30	0.037	9.4	0.011	44	0.054	16	0.020
30	02321975	SANTA FE RIVER AT US HWY 441, NR HIGH SPRINGS, FL	859.0	260	0.303	92	0.107	290	0.338	98	0.114
31	02322000	SANTA FE RIVER NR HIGH SPRINGS, FL	868.0	226	0.260	83	0.096	255	0.294	89	0.103
32	02322240	SANTA FE RIVER BL LILLY SPRING, NR FORT WHITE, FL	977.0	--	--	--	--	--	--	--	--
33	02322500	SANTA FE RIVER NR FORT WHITE, FL	1,020.0	964	0.945	736	0.722	993	0.974	751	0.736
34	02322540	SANTA FE RIVER AT SR 47, NR FL FORT WHITE, FL	1,030.0	--	--	--	--	--	--	--	--
35	02322590	COW CREEK NR FORT WHITE, FL	89.0	0.9	0.010	0.6	0.007	1.1	0.012	0.7	0.008
36	02322660	ROSE CREEK NR COLUMBIA, FL	26.2	0.0	0.000	0.0	0.000	--	--	--	--
37	02322700	ICHETUCKNEE RIVER NR HILDRETH, FL	e200.0	310	1.550	240	1.200	320	1.600	250	1.250
38	02322800	SANTA FE RIVER NR HILDRETH, FL	1,370.0	1,580	1.150	1,140	0.832	1,620	1.180	1180	0.861
39*	02323000	SUWANNEE RIVER NR BELL, FL	9,390.0	4,120	0.439	2,960	0.315	4,260	0.454	3030	0.323
40*	02323500	SUWANNEE RIVER NR WILCOX, FL	9,640.0	5,260	0.546	4,020	0.417	5,500	0.571	4180	0.434

Station name	-	Indented name denotes tributary to the above order stream
( )	-	estimated values based on comparison of measurement and low-flow frequency data
e	-	estimated
<	-	less than
>	-	greater than
*	-	not included in figure 3

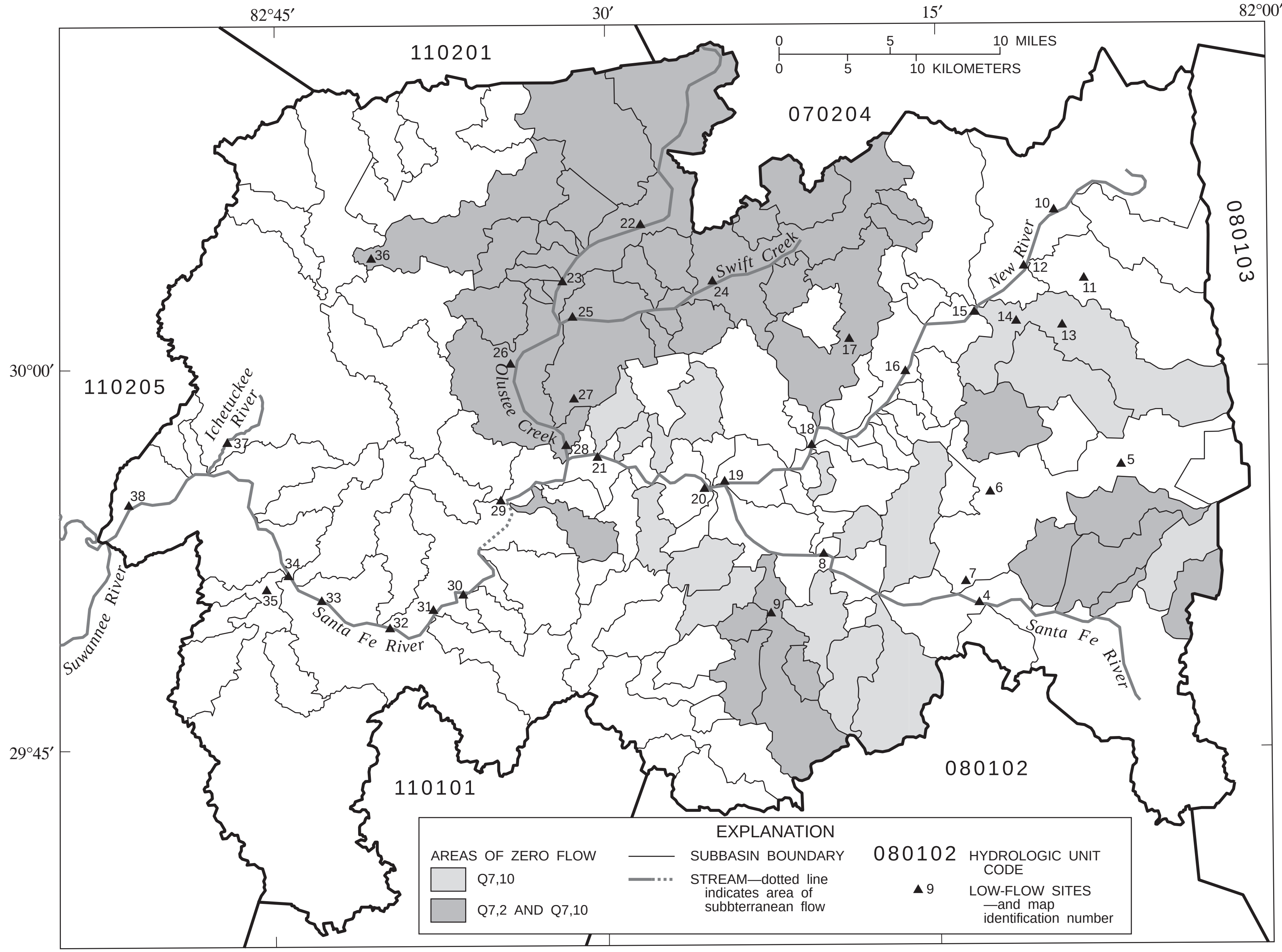

Figure 3. Location of sites in the Santa Fe River basin used to develop a method for estimating low-flow characteristics at ungaged sites.

Development of Method for Estimating Low-Flow Characteristics

Measurement data collected during the synoptic-measurement runs show low-flow conditions during runs 1-4 to be within the range of 94 to 99 percent flow duration at Graham, Worthington Springs, and Ft. White; and for run 5, 60 to 90 percent. With respect to a 7-day low flow, runs 1 and 3 represent a 4-year low-flow recurrence interval; runs 2 and 4, a 10-year; and run 5, a low-flow condition that would be expected to occur on the average of once a year. The daily streamflow pattern for three sites on the Santa Fe River, at Graham, at Worthington Springs, and near Fort White, during low-flow climatic period, April 1989 to March 1992, is shown on figure 4.

The location of sites of synoptic measurement data were plotted on basin maps and noted where significant changes in flow occurred within the basin. Factors that may cause these changes in flow include changes in ground-water flow systems and the impact of changes in flow at springs and sinks within the river system. As an example, decreases in flow in a downstream direction (rather than expected increases) were observed, based on the plotted data, on the Santa Fe River between Worthington Springs and Bland (river mile 51 and 43); on the lower reaches of the New River near Lake Butler and Worthington Springs (river mile 14 and 1); and on the Olustee Creek below Swift Creek tributary (river mile 10). These changes are suspected to be the result of the water table in the surficial aquifer falling below the stage of the rivers, allowing water in the river to discharge into the underlying aquifer.

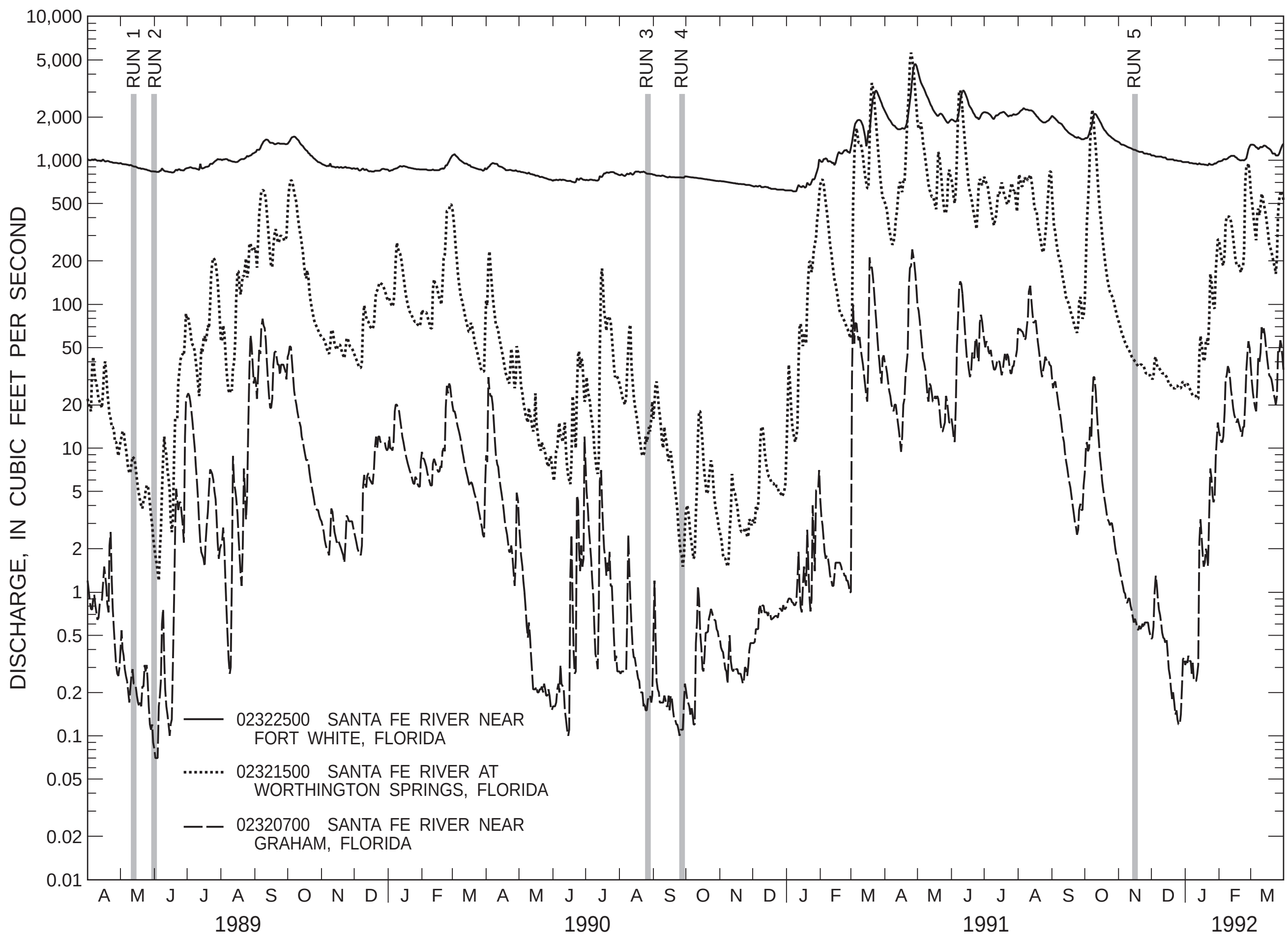

Figure 4. Daily-record streamflow for 1989-92 for three sites on the Santa Fe River and noted periods of five synoptic runs.

Low-flow frequency characteristics and drainage areas determined at specific sites were used to define river profiles for the entire reaches of the Santa Fe and New Rivers and Olustee Creek (fig. 5). Low-flow profiles were constructed by interpolation or extrapolation from points representing sites where low-flow data have been determined, and plotted against miles from the mouth of the river. Low streamflows generally have a close relation to drainage area, especially on the same stream. Profiles or data available to construct profiles, are used as a guide for noting changes in the stream's characteristics in the different reaches of the stream. These river profiles serve as indicators of changes in river flows with respect to change in drainage area.

Unit low flows were defined for each site where low-flow characteristics were determined and a drainage area was defined. Unit low flows are defined by dividing the low-flow characteristic ($Q_{N,T}$) by the drainage area at a particular site. Changes in unit flows along the reach of the river may denote changes in basin characteristics affecting the flow within a prescribed reach of the river or change caused by the additional flow from a tributary having different stream characteristics than the main stream.

Areas of zero flow were defined for $Q_{7,2}$ and $Q_{7,10}$ conditions based on measurements made during the five synoptic runs in 1989-91 and one synoptic run (by Hunn) in 1977, and from low-flow frequency analyses. Zero flow occurs commonly in the tributary streams in the surficial aquifer and in the areas where the confining beds come in contact with the Upper Floridan aquifer. Zero flow is not evident in areas where streams are in contact with the Upper Floridan aquifer. About one-third of the basin area experiences zero flows during critical low-water conditions.

Application of Method

A flow-routing method was used to estimate low-flow characteristics at ungaged sites in the Santa Fe River Basin from low streamflow analyses based on records at gaged sites. The use of the flow-routing method is suggested for areas where regression analysis proves unsuccessful, where low-flow characteristics have been defined at a significant number of sites, and where information of the basin characteristics (factors that affect low flows) has been thoroughly researched.

This method uses the drainage areas to interpolate low-flow values between or near gaged sites on the same stream. Unit discharges are used as an indicator of changes in uniform flow along the reaches of the stream, and may denote changes in the basin characteristics. Low-flow values are transferred from a gaged site, either upstream or downstream, to the ungaged site. When it is necessary to proceed beyond a confluence, low-flow values are estimated to a point at the confluence, or other noted change in flow, then adjustments to the initial calculation should be made to compensate for the change (addition or subtraction) of flow. This procedure is continued until the location of the ungaged site is reached.

This method can be used for streams that cross different basins or different water-bearing zones, a characteristic which commonly occurs in the Santa Fe River Basin. Changes in basin characteristics can alter the low-flow characteristics of a stream; therefore, when applying the flow-routing method judgment should be used when basin characteristics change significantly between the gaged and the ungaged sites. Changes in unit discharges, presented in table 3, serve as indicators of change in basin characteristics that control flow to the stream.

To determine the low-flow values at an ungaged site on a stream between two gaged sites, the following steps should be taken: (1) locate the nearest gaged sites, (2) determine the drainage area for the ungaged site between the gaged sites, and (3) multiply the low-flow value at the gaged site by the drainage area of the ungaged site and divide by the drainage area of the gaged sites. The flow-routing equation for estimating low-flow characteristics consists of a simple drainage-area ratio, where

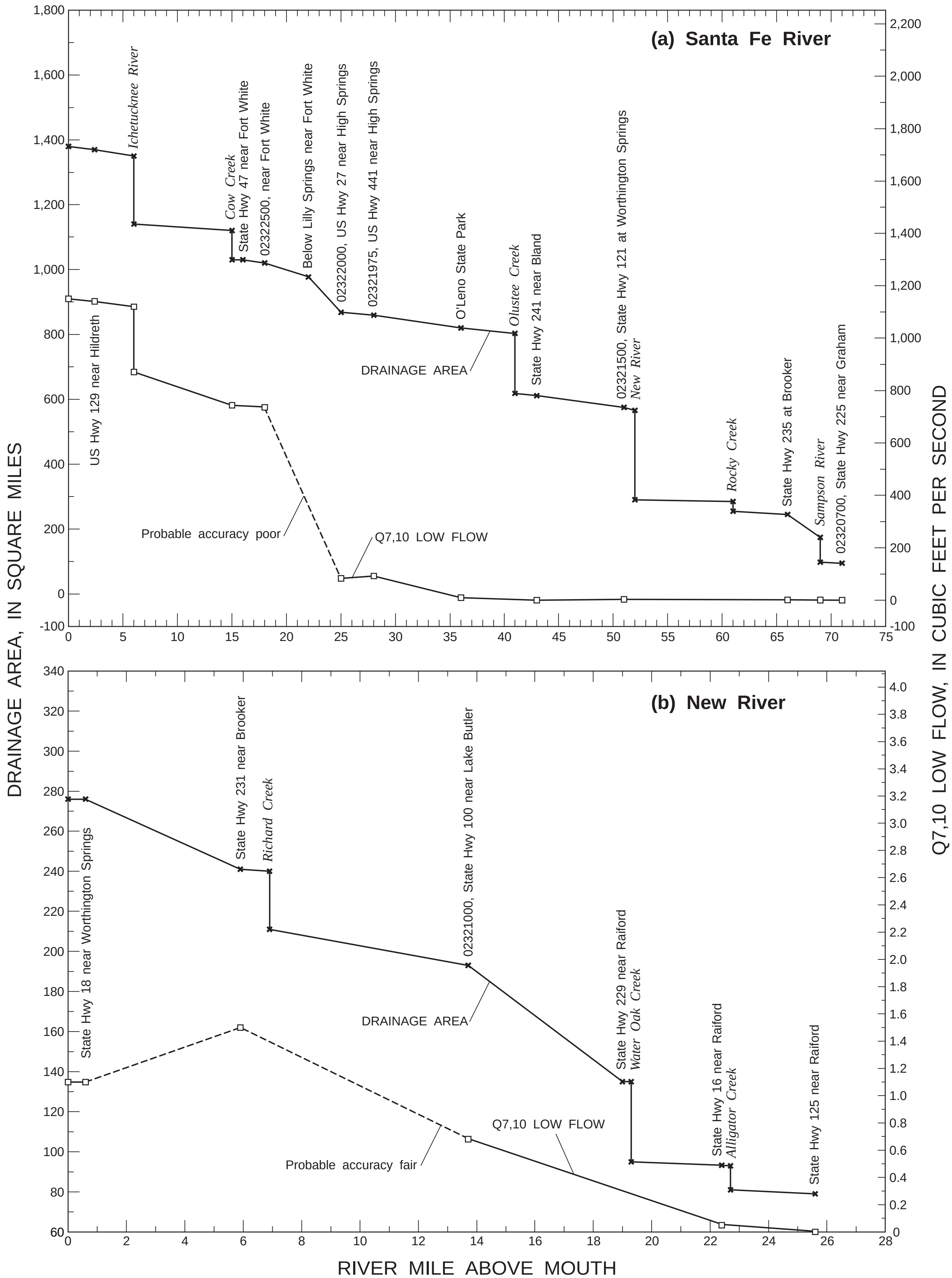

Figure 5. River profiles of the Santa Fe River, New River, and Olustee Creek.

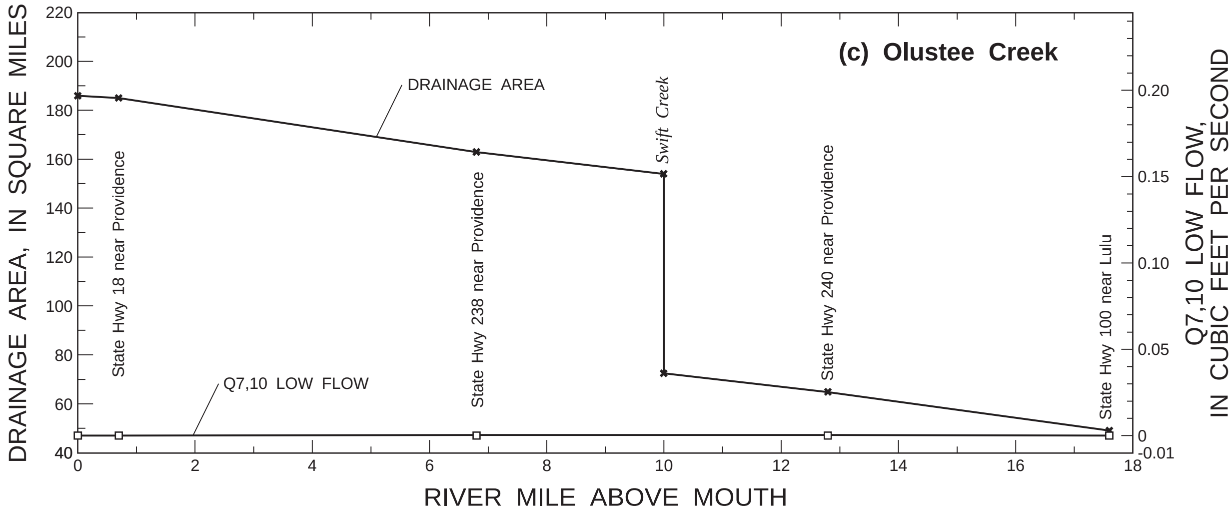

Figure 5. River profiles of the Santa Fe River, New River, and Olustee Creek--continued.

$$Q_{N,T}\ ungaged\ site\ =\ \frac{Q_{N,T}\ gaged\ site \times DA\ ungaged\ site}{DA\ gaged\ site} \qquad (26)$$

where,

$Q_{N,T}$ = average minimum N-consecutive-day low flow having a T-year recurrence interval, in cubic feet per second and;

DA = drainage area, in square miles.

A review of available geologic (surficial and hydrogeologic) and topographic maps could provide information on the stream's characteristics that may be useful in the analysis. The following examples show the use of the flow-routing method. Figure 3 shows the general location of gaging sites where low-flow characteristics have been determined, and table 3 presents the low-flow value and drainage area for each gaged site. The simplest determination of estimated low-flow values is made when no major tributaries or other inflow (springs) and outflow (sinks) enter or leave the stream at any points between the gaged and ungaged sites.

Example--Determine the $Q_{7,2}$ and $Q_{7,10}$ for the ungaged site on the New River having a drainage area of 160 mi^2. Using table 3 the low-flow characteristics at nearby gaged site, New River near Lake Butler (site16), are routed upstream to the ungaged site using equation 26:

from table 3, the drainage area of site 16 is 193 mi^2 and $Q_{7,2}$ is 2.1 ft^3/s.

$$Q_{7,2} = \frac{2.1 \times 160}{193} = 1.7\ ft^3/s$$

from table 3, $Q_{7,10}$ is 0.68 ft^3/s

$$Q_{7,10} = \frac{0.68 \times 160}{193} = 0.56\ ft^3/s\ .$$

A review of surficial geologic (Knapp, 1978; Hunn and Slack, 1983) and USGS topographic maps indicates there are no major changes in the basin characteristics between the two gaged sites that would influence predictive flows between sites.

A more complex flow-routing analysis must be performed to estimate low-flow characteristics at the ungaged site when tributary or other flow enter a stream. The user should have a working knowledge of the low-flow characteristics of the tributary streams that are needed for the analysis. In a tributary stream where low-flow conditions reach zero flow, a common occurrence in the eastern portion of the Santa Fe River Basin, the drainage area for that tributary should be considered as a non-contributing area in the analysis.

Example--To estimate the 2-year and 10-year low flows for a 7-day recurrence at the location where Wilson Springs Road crosses the Santa Fe River (11 miles above the mouth), data from three of four sites must be used: Santa Fe River near Fort White (site 33), Cow Creek near Fort White, (site 35), Ichetucknee River near Hildreth (site 37), and Santa Fe River near Hildreth (site 38). Two approaches for estimating low flow at Wilson Springs Road may be considered. First, using the flow-routing method in equation 26, route the flow downstream from the gaged site at Santa Fe River near Fort White to the confluence of Cow Creek, and downstream for the gaged site at Cow Creek near Fort White to a point at their confluence and add the flows; then proceed downstream, using equation 26, to the ungaged site where Wilson Springs Road crosses the Santa Fe River. In a second approach, using equation 26, route the flow upstream from the gaged site at Santa Fe River near Hildreth to the confluence of the Ichetucknee River, and downstream from the gaged site at Ichetucknee River near Hildreth to its mouth, and subtract the flows to determine the flow at that point (confluence); then, proceed upstream using equation 26 to the ungaged site where Wilson Springs Road crosses the Santa Fe River.

Approach 1: The $Q_{7,2}$ for Santa Fe River above the confluence of Cow Creek is calculated from the $Q_{7,2}$ value at Santa Fe River near Fort White as follows:

$$Q_{7,2} = \frac{964 \times 1,030}{1,020} = 973\ ft^3/s\ .$$

The $Q_{7,2}$ at the mouth of Cow Creek is calculated from the $Q_{7,2}$ value at Cow Creek near Fort White as follows:

$$Q_{7,2} = \frac{0.9 \times 94}{89} = 1.0\ ft^3/s\ .$$

The $Q_{7,2}$ value at the confluence of the Santa Fe River and Cow Creek is determined by adding the estimated values, where:

$$Q_{7,2} = (973 + 1) = 974\ ft^3/s$$
$$DA = (1,030 + 94) = 1,120\ mi^2.$$

Drainage areas for the Santa Fe River and Cow Creek at the confluence are also added (or determined for that point on the river) for use in the process to continue the flow routing to the point where Wilson Springs Road crosses the Santa Fe River. Using equation 26, the routing is as follows:

$$Q_{7,2} = \frac{974 \times 1,130}{1,120} = 982\ ft^3/s\ .$$

Approach 2: In this approach, the flow routing begins from a gaged site located downstream from the ungaged site at Wilson Springs Road. The $Q_{7,2}$ value for the Santa Fe River below the confluence of the Ichetucknee River is calculated using the $Q_{7,2}$ value from the Santa Fe River near Hildreth as follows:

$$Q_{7,2} = \frac{1,580 \times 1,350}{1,370} = 1,557\ ft^3/s\ .$$

The $Q_{7,2}$ at the mouth of the Ichetucknee River is calculated from the $Q_{7,2}$ at the Ichetucknee River near Hildreth as follows:

$$Q_{7,2} = \frac{310 \times 210}{200} = 325\ ft^3/s\ .$$

The $Q_{7,2}$ value at the confluence of the Santa Fe and Ichetucknee Rivers is determined by subtracting the estimated values, where:

$$Q_{7,2} = (1,557 - 325) = 1,232\ ft^3/s$$
$$DA = (1,350 - 210) = 1,140\ mi^2.$$

Using equation 26, flow routing is continued to the ungaged site where Wilson Springs Road crosses the Santa Fe River.

$$Q_{7,2} = \frac{1,230 \times 1,130}{1,140} = 1,220\ ft^3/s\ .$$

The difference in the results of these two approaches is 22 percent. The results for estimating the $Q_{7,10}$ values for the ungaged site at Wilson Springs Road using the above two approaches are 751 and 863 ft^3/s, or a difference of 14 percent. These percent differences do not reflect the percent error of the estimated low-flow values but serve to show error as a difference from using two separate approaches.

The accuracy of the method was checked by applying the flow-routing method used in example 2, where $Q_{7,2}$ was used for the gaged site at Santa Fe River near Fort White (site 33) and routed a distance of 16 miles to the gaged site at Santa Fe River near Hildreth (site 38). The results of the flow routing for $Q_{7,2}$ at Hildreth is 1,330 ft^3/s, or 15 percent less than low-flow values of 1,580 ft^3/s determined from streamflow records collected at this site; and, for $Q_{7,10}$, 1,000 ft^3/s, or 12 percent less than the value of 1,140 ft^3/s determined from streamflow records.

A weighted average of the drainage areas may also be considered in the analysis when an ungaged site is located between two gaged sites. The low-flow value at the ungaged site may be estimated by using a weighted average of estimates from the two gaged sites as in the following equation:

$$Q_{N,T}un = \frac{DA\ un - DA\ up}{DA\ dn - DA\ up}(Q_{NT}, dn) + \frac{DA\ dn - DA\ un}{DA\ dn - DA\ up}(Q_{NT}, up) \qquad (27)$$

where,

$Q_{N,T}$ = average minimum N-consecutive-day low flow having a T-year recurrence interval, in cubic feet per second and;

DA = drainage area, in square miles.

un = ungaged site

up = upstream gaged site

dn = downstream gaged site

The weight of the estimate at each gaged site is 100 percent, diminishing to 0 percent at distances upstream and downstream (Giese and Mason, 1993).

The strength of the flow-routing method is that the values at gaged sites reflect the overall basin characteristics in the vicinity of the gaged sites. These values can be transferred upstream and downstream for a short distance within a basin and still maintain similar basin characteristics. As noted in table 3, similar values in unit discharge may indicate areas of similar basin characteristics, factors that influence low flows.

In this study area, varied flow conditions exist and should be considered when using the flow-routing method. In the above example, the total flow in the Cow Creek Subbasin is negligible to the flow in the Santa Fe River at that point; in smaller drained tributary streams, routing is not necessary. Figure 3 shows areas (subbasins) of zero flow when low-flow conditions are at $Q_{7,2}$ and $Q_{7,10}$. The accuracy of low-flow estimates may be less if sufficient data are not available to assess conditions in areas of decreasing flow, such as sinks (located between sites 30 and 31 on the Santa Fe River), and change in the ground-water flow system (where the water table in the surficial aquifer falls below the stage of the New and Santa Fe Rivers and Olustee Creek); and areas of increasing flow, such as near spring discharge to the stream (between sites 29 and 30 on the Santa Fe River below O'Leno State Park) and near tributaries having significantly different stream characteristics.

In areas where sufficient low-flow characteristics are available from long-term gaging sites, unlike the Santa Fe River Basin, flow-routing equations may be developed in a regression analysis that uses drainage areas and location of site where low-flow values have been determined. Hayes (1991) presents a flow-routing method for streams in Virginia for 77 paired sites that include limits on distance for routing and accuracy of estimated values at ungaged sites.

Summary and Conclusions

Methods for estimating low-flow frequency characteristics at ungaged sites were developed for two areas in northern Florida. In the Yellow, Blackwater, Escambia, and Perdido River Basins study area in northwestern Florida, regional regression equations were developed for estimating the 7- and 30-day, 2- and 10-year low-flow characteristic ($Q_{7,2}$, $Q_{7,10}$, $Q_{30,2}$, and $Q_{30,10)}$ by determining values of basin characteristics from digital Geographical Information System (GIS) coverages or hardcopy maps. A GIS, ARC-INFO, was used to quantify basin characteristics that were used in regression equations. Several sources of digital data were used in this analysis: elevation data, from a digital elevation model, stream length and location data were obtained by selecting stream features from a digital hydrography coverage, and watershed boundaries were digitized from delineations made on USGS 7.5-minute topographic maps.

Several hydrologically-based basin characteristics were derived from geomorphic basin descriptions and identified as possible predictors of low-flow characteristics. The most accurate regression equations employed a basin characteristic that was based on a simple conceptual model of one-dimensional ground-water flow using Darcy's law. Slightly less accurate equations were obtained using drainage area as the only explanatory variable. The standard error of prediction for the Darcy and drainage area equations of $Q_{7,10}$ was 65 and 74 percent, respectively; $Q_{7,10}$, 58 and 62 percent, respectively; $Q_{30,2}$, 51 and 54 percent, respectively; and $Q_{30,10}$, 44 and 51 percent, respectively.

Caution should be used when applying regression analysis using the developed models outside of the Yellow, Blackwater, Escambia, and Perdido River Basins. The chief reason for this limitation is that these equations are dependent on the hydrogeologic, and climatic characteristics of this region. Neither of these factors is accounted for by the explanatory variables, Q_{Darcy,A_d} and A_d. Therefore, large errors could result if the hydrogeology and climate of an ungaged basin are significantly different than that in the basins used to fit equations 8-15.

In the Santa Fe River Basin study area in northeastern Florida, a flow-routing method was used to estimate low-flow characteristics at ungaged sites from low streamflow analyses based on records at gaged sites. The use of the flow-routing method is suggested for areas where regression analysis proves unsuccessful, where low-flow characteristics have been defined at a significant number of sites, and where information of the basin characteristics has been thoroughly researched.

Low-flow frequency characteristics were determined at 20 sites in a previous study, and 20 additional sites based on data collected during the synoptic-measurement runs during 1989-91. These measurements were used to develop a flow-routing method for estimating low flows within the basin. Data used in the analysis for low-flow characteristics at each station were from the beginning of record to 1994.

Low-flow frequency characteristics and drainage areas determined at specific sites were used to define river profiles for major streams within the basin. Unit low flows were also defined for each site where low-flow characteristics were determined. These river profiles and unit low flows serve as indicators of changes in the stream's low-flow characteristics with respect to change in drainage area.

The flow-routing method uses the drainage areas to interpolate low-flow values between or near gaged sites on the same stream. Low-flow values are transferred from a gaged site, either upstream or downstream, to the ungaged site. A step-by-step process for flow routing must be made when tributary or other inflow enters a stream. Knowledge of the low-flow characteristics of the tributary stream is needed for the analysis.

The strength of the flow-routing method is that the values at gaged sites reflect the overall basin characteristics in the vicinity of the gaged sites. These values can be transferred upstream and downstream for a short distance within a basin and still reflect the basin characteristics. The accuracy of low-flow estimates may be less in areas of decreasing and increasing flows if sufficient data are not available to assess changing hydraulic and hydrologic conditions.

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